Wrapping Up Greenhouse Gas Emissions

An Assessment of GHG Emission Reduction Related to Efficient Packaging Use

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Summary

The use of packaging materials results in greenhouse gas (GHG) emissions through production and transport of materials and packaging and through end-of-life management. In this article, we investigate the potential reduction of GHGs that are related to packaging. For this purpose, we use the dynamic MATTER-MARKAL model in which the western European energy and materials system is modeled. The results show that GHGs related to packaging can technically be reduced by up to 58% in the period 1995±2030. Current European packaging directives will result in a 10% emission reduction. Cost-effective improved material management[1] that includes lightweighting, reusable packages, material recycling, and related strategies can contribute a 22% GHG emission reduction. An additional 13% reduction becomes cost effective when a GHG emission penalty of 100 euros per metric ton[2] (EUR/ton) is introduced (1 EUR ≈ 0.9 USD). Generally speaking, improved material management dominates the gains that can be achieved without a penalty or with low GHG emission penalties (up to 100 EUR/ton CO_2 equivalent). By contrast, the reduction of emissions in materials production and waste handling dominate when high GHG penalties are applied (between 100 and 500 EUR/ton CO_2 equivalent). Given the significant technical potential and the low costs, more attention should be paid to material efficiency improvement in GHG emission reduction strategies.

Introduction

Greenhouse gas (GHG) emission reduction is one of the key environmental problems for sustainable development in the 21st century. In 1997, targets and timetables were set at the third Conference-of-the-Parties to the United Nations Framework Convention on Climate Change in Kyoto to reduce the emission of GHGs. The member states of the European Union have jointly agreed on a reduction of 8% of the emission of the six most important GHGs[3] over the period 2008–2012 as compared with the 1990 emissions (UNFCCC 1997). Further reductions will be required beyond this period to reach stabilization of global GHG concentrations at acceptable levels as called for by the U.N. Climate Convention. Most probably, a reduction by 50% to 80% in the next 50–100 years will be required in industrialized countries in order to keep GHGs at acceptable concentration levels (Houghton 1996; Turkenburg 1997).

Table 1 shows the total GHG emissions of western Europe for the reference year,[4,5] expressed in carbon dioxide (CO_2) equivalents.[6] CO_2 constitutes approximately 80% of total GHG emissions. Methane (CH_4) and nitrous oxide (N_2O) constitute the bulk of the non-CO_2 GHG emissions in the reference year. The emissions of both gases are expected to decline autonomously until 2010 because of changing process technology in the chemical industry, a decrease in coal mining, and decreased landfilling of waste. The relevance of hydrofluorocar-

bons (HFCs) will increase in the next decade because of the ongoing substitution of chlorofluorocarbons (CFCs) with HFCs. Perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) emissions remain relatively insignificant.

Several options for GHG emission reduction exist. One of these is improving the efficiency of energy use. Other options include, for instance, increasing the use of energy from clean, renewable resources, and applying end-of-pipe technology for the removal and storage of CO_2. A large part of primary energy use is related to the production of materials. A limited number of materials constitute the bulk of this energy use and the associated GHG emissions. Table 2 provides an overview of these materials and the associated emissions for production and waste handling for the year 1995 related to the western European situation. Comparing table 1 with table 2 shows that approximately one-quarter of the total western European GHG emissions can be attributed to the production of these bulk materials.[7]

The emissions related to the consumption of materials can be reduced by implementing emission reduction options in the production processes of these materials. They can also be reduced through changes in the use of materials. Improved management of material use has been studied and practiced mainly from the perspective of waste reduction. Little attention has been given to material management strategies focused on GHG emission reduction.

Only a few studies have been published dealing with this issue. One study has been done for the Netherlands (Gielen 1995). This study showed a significant emission reduction potential, but it identified major barriers to emission reduction because of international trade. In 1998, a U. S. Environmental Protection Agency study was published on GHG emissions from management of materials in municipal solid waste (USEPA 1998). The study shows that life-cycle management of materials presents many opportunities for GHG emission reduction. Although this study focuses on the relationship between material use and GHG emissions, it emphasizes waste management. A detailed investigation of options for improved material management in the production and consumption stage of products was not carried out. Moreover, costs were

Table 1 Emissions in the reference year, western Europe

Category		Emission in reference year (MMT CO_2 equivalent)
CO_2	Carbon dioxide	3,323
CH_4	Methane	500
N_2O	Nitrous oxide	350
HFCs	Hydrofluorocarbons	42
PFCs	Perfluorocarbons	13
SF_6	Sulfur hexafluoride	15
Total		4,243

Source: Gielen (1999).

Table 2 The annual emissions of GHGs in western Europe in 1995 as a result of the production and waste handling of materials, calculated following Intergovernmental Panel on Climate Change accounting guidelines

	CO_2 (MMT CO_2 equiv.)	Non-CO_2 GHG (MMT CO_2 equiv./yr)	Total (MMT CO_2 equiv./yr)	Fraction (%)
Metals	244	11	255	26
Synthetic organic materials	167	53	220	22
Natural organic materials	93	130	223	22
Inorganic materials	49	60	109	11
Ceramic materials	191	–	191	19
Total	744	254	998	100

Source: Gielen (1998); see IPCC (1998) for accounting guidelines.

Note: These figures include energy use for primary and secondary material production plus the emissions associated with waste management. Excluded is the energy use in all other life-cycle stages such as raw material acquisition, transport, product manufacturing, and maintenance.

not considered in the analysis of the policy relevance of waste management strategies.

Two studies describe how more improved material management may lead to a reduction in energy use. In a study by Worrell and colleagues (1995a), the focus is on energy savings due to more efficient use of fertilizer, and in a different study by Worrell and colleagues (1995b), an approach is described for analyzing the potential of material efficiency improvement that was tested on plastic packaging in the Netherlands. Both studies show that in these specific cases, there is significant potential for reducing CO_2 emissions by improving material management. Many studies are available that focus on the potential for increased efficiency of materials use from an environmental perspective, such as those by Beukers and Hinte (1998) and Brezet (1994); however, these studies have a generic product design perspective and do not specifically focus on GHG emission reduction.

To provide more insight into the potential for reducing GHG emissions in western Europe through changes in the life cycle of materials, a project called MATTER (materials technologies for greenhouse gas emission reduction) was started; it was coordinated by the Netherlands Energy Research Foundation.[8] Western Europe has a more closed materials system with limited exchange with other regions (Gielen 1998). As a consequence, a European materials policy may be more viable than a Dutch materials policy.

One of the product groups studied in the MATTER project is packaging. There are three reasons for this. First, changes in material use for packaging are an interesting study object because packaging is already subject to waste management policies such as the European Packaging Directive (EU 1994). These policies will have an impact on GHG emissions, and it is interesting to investigate what this impact could be. Therefore, the effect of existing packaging legislation on western European GHG emissions can serve as a case study for investigating the impact of existing environmental policies on GHG emissions. Second, packaging materials constitute a significant section of the total materials market; in 1995 about 75 million metric tons (MMT) per year of material was used for packaging purposes in western Europe, which equals about 10% of the total quantity of western European materials (Duin 1997; Hekkert et al. 2000a).

The third reason is that in various international public policy forums, the question arises whether significant environmental improvements are more likely to be obtained through improvements to core infrastructure (e.g., energy and feedstock supply and waste management) rather than through improvements of specific product chains (see, e.g., Fonteyne et al. 1998).

This question can be answered by means of a model where both types of improvements are considered. Earlier studies that have been carried out within the MATTER project have already shown that improved management of packaging materials can technically reduce the CO_2 emissions related to packaging by about 40% to 50% (see Hekkert et al. 2000a, 2000b). These studies have focused solely on improved material management in the packaging life cycle, and they take the current energy and materials systems configuration as a reference. Changes in core infrastructures and measures such as more efficient energy use for material production have not been considered. To investigate long-term strategies to reduce GHG emissions, an integrated energy and materials systems analysis is needed, because different reduction strategies influence one another's effectiveness. For example, if all power producers switch from fossil fuels to GHG-free renewables, electricity production by waste incineration no longer contributes to GHG emission reduction. Furthermore, a dynamic approach is needed because significant GHG emission reduction will take decades. Changing technology, changing consumption patterns, changing resource prices, and changing environmental policy goals are issues that must be considered within such a time frame. A static analysis of emission reduction potential may result in misleading answers, where long-term significant emission reduction is the goal. Based on these two criteria, the MATTER-MARKAL model is designed for long-term policy design. It is a dynamic integrated model where both the energy and materials systems are modeled. In particular, new technology has been dealt with in great detail.

In this article, we present an integrated analysis of GHG emission reduction measures in all stages of the materials life cycle for packaging materials. This analysis reflects only a portion of the total modeling results because the model encompasses many other product groups besides packaging. Integrated analysis refers in this case to an investigation of the full materials' life cycle "from cradle to grave," taking into account all categories of GHGs and considering the potential impact of a broad variety of improvement options (see the section on the model structure).

Integrated analysis also means that the interaction between the materials and the energy system are taken into account. We focus on the following five questions:

1. What will be the future relationship between packaging and GHG emissions?
2. To what extent are GHG emission reductions based on changing materials management affected by GHG emission reductions in other parts of the energy and materials system?
3. What is the contribution of current European waste directives to future reductions of GHG emissions?
4. How do the costs of improved material management options compare with the costs of other GHG emission reduction options?
5. What changes in material use will occur in the case of stringent GHG policies?

To answer these questions, we first present an overview of the relationship between packaging materials and GHG emissions. Next we describe the model characteristics and the model input data, followed by model results and conclusions.

Packaging and GHG Emissions

Many different materials are used for the production of packaging. The material choices depend on the desired characteristics of the packaging material, such as barrier properties and strength, as well as marketing considerations. In table 3, the materials most often used are listed, and the related GHG emissions due to material production and waste management are estimated. Emissions in other life-cycle stages such as packaging manufacturing, cleaning, and transportation are not accounted for because they depend more on the products that are made from the basic materials than on the materials themselves.

Table 3 shows that, in 1994, the total GHG emissions related to the materials used for packaging in western Europe was 144 MMT. This is 3.3% of the total GHG emissions in western Europe. CO_2 emissions dominate, but non-CO_2 emissions are also relevant, especially CH_4 emissions from disposal sites. In table 3, this is in-

Table 3 Material consumption for western European packaging and associated GHG emissions in 1994 in MMT per year

	Consumption	Recycling rate	CO_2 emission	Other GHG emission[*] (CO_2 equiv.)	total GHG emission (CO_2 equiv.)
Paper and board	28	50%	14	24	38
Glass	17	50%	8	0	8
Plastics	12	0%	50	0	50
Metals	6	50%	25	8	32
Others[†]	13	25%	10	5	15
Total	75		107	37	144

Sources: APME (1996), Duin (1997), and Gielen (1998).

[*]Includes CH_4 emissions from disposal sites for paper and board and for wood; perfluorocarbon emissions for aluminum production.

[†]Includes wood.

cluded as "other GHG emissions" due to paper and board consumption. The amount of recycled material is estimated, based on recycling statistics for individual packaging types and materials. Recycling is important because recycling of materials generally results in considerably lower GHG emissions than production of materials from natural resources. The remaining waste fraction is either incinerated or landfilled. On average, 80% of all municipal solid waste in western Europe is still disposed of; the remaining 20% is incinerated (about 15% is incinerated with energy recovery, and this recovery is not accounted for in table 3[9]) (Rijkema 1993). The emissions for plastics are based on actual emission accounting. Synthetic carbon storage (the storage of carbon present in oil-derived plastics) in disposal sites is not accounted for as emission, in line with Intergovernmental Panel on Climate Change (IPCC) emission accounting guidelines. For paper and other natural organic materials, no carbon storage is accounted for upon disposal, also in line with these guidelines.

Whereas paper and paperboard are generally considered environmentally benign materials because of their origin from renewable biomass, the GHG balance is influenced by the methane emissions in the waste disposal stage. The high GHG emission for metal packaging is mainly related to aluminum packaging. Whereas recycling rates for beverage cans are high in some European countries,[10] aluminum foils and laminates are virtually not recycled because of high costs and high energy use for their collection. This is important because the GHG emissions for primary aluminum are 10–20 times higher than for secondary aluminum). Aluminum foil for packaging is made from primary aluminum.

For a proper comparison of the GHG impact of different packaging materials, the packaging service must be considered. Packaging service is the amount of product that can be packed by a certain amount of packaging material. It is used in the same manner as the concept of a functional unit in life-cycle assessment; it makes it possible to compare the characteristics of different packaging materials. An example of a packaging service is packing 1000 L of product. The packaging service of a ton of plastics is generally 5–10 times higher than the same packaging service delivered by a ton of paper, board, or glass because fewer kilograms of plastics are necessary to pack 1000 L of products. On a service basis, plastics constitute the most important packaging material. As a consequence, the emissions per service unit for plastics are 5–10 times lower (Hekkert et al. 1998).

The Model Structure

The MATTER-MARKAL Model

The MATTER-MARKAL model is a representation of a part of the western European econ-

omy. The economy is modeled by a network of processes and by physical and monetary flows between these processes. The processes represent all activities that are necessary to provide products and services. Many products and services can be generated through a number of alternative (sets of) processes. The model contains a database of more than 1,000 processes, covering the total life cycle for both energy and bulk materials with GHG relevance (figure 1). The model calculates the least-cost system configuration. In the MATTER-MARKAL model, GHG emissions are endogenized in the optimization through the introduction of emission penalties.[11]

The time span to be modeled is divided into nine periods of equal length, generally covering a period of decades. The model is used to calculate the least-cost system configuration for the total time period, meeting exogenously defined product and service demands and emission reduction targets. This optimization is based on a so-called perfect foresight approach, where all time periods are optimized simultaneously. Future constraints are taken into account in current investment decisions. The growth of economic activity is modeled by increasing product and service demand figures.

MARKAL was originally developed as an energy systems analysis tool. The modeling approach has been extended to materials system analysis from cradle to grave (Gielen 1995). Figure 2 shows the life-cycle structure for materials and products. The model covers more than 25 energy carriers and 125 materials. More than 50 products represent the applications of these materials. Thirty categories of waste materials are modeled.

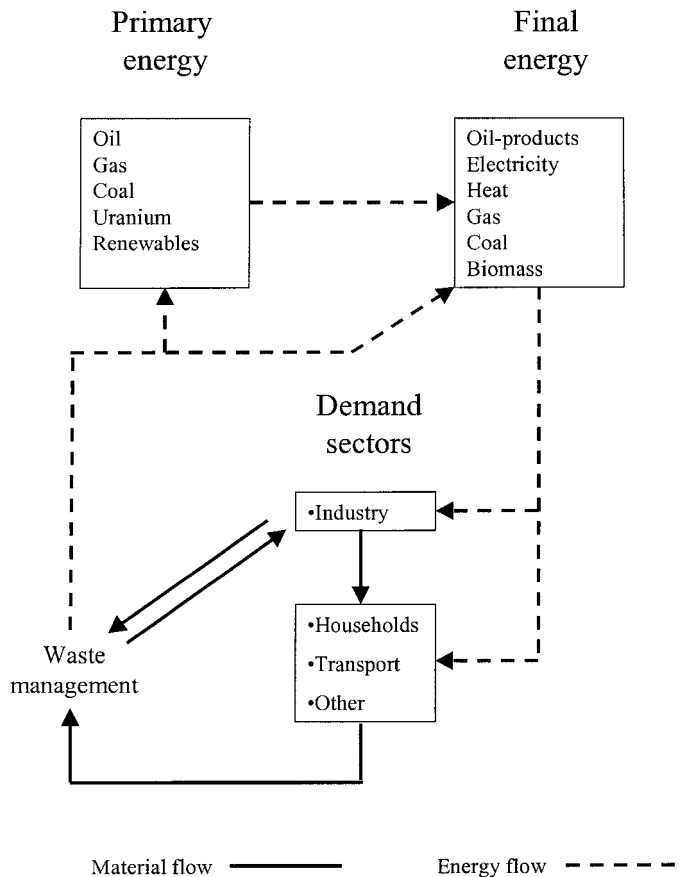The modeling results for the packaging sector are influenced not only by the model input for

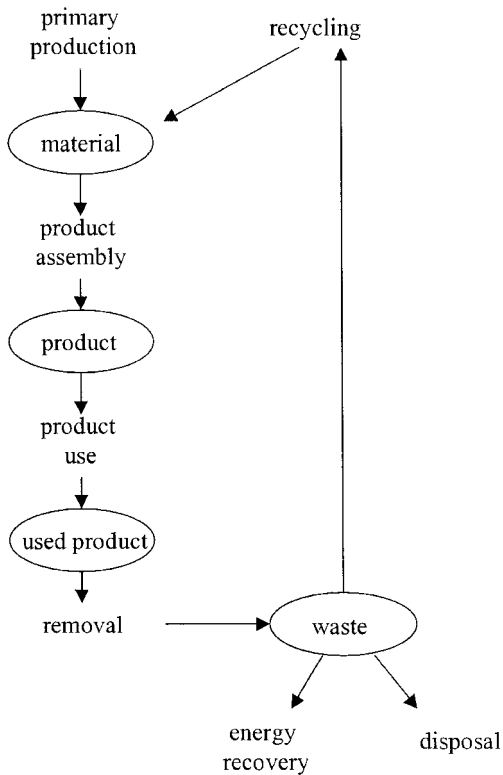**Figure I**   Generic MARKAL energy and materials system model structure (Gielen 1999).

Material flow ——————   Energy flow – – – – –

Figure 2   Materials system model structure.

a great influence on the model output. In addition to some general parameters such as energy prices and gross domestic product developments, the potential for some technical GHG emission reduction options and their costs are stated in generic terms.

The Model Structure for Packaging

To model current and future demand for packaging materials in the MATTER-MARKAL model, three types of information are fed into the model. First, the current and future demand for packaging products are defined. Second, the current packaging technology required to fulfill the demand for packaging products is described. Third, future options for improved material used to fulfill the future demand for packaging products are indicated. We now describe the model structure for packaging based on this categorization.

Current and Future Demand for Packaging

To pack a specific product, several types of packaging can be used. Milk, for example, can be packed in liquid board packages or in plastic bottles, and the plastic bottles can be packed in either cardboard boxes, plastic crates, or stretch film. To be able to model all these substitutions, a demand for packaging services is modeled instead of a demand for packages. Because each specific packaging service cannot be modeled because of the wide variation in character and composition, all services are categorized into a few representative groups. The categorization is based on specific characteristics of the packages that are necessary to fulfill a service. For example, we distinguish packaging to pack liquids from packaging to pack dry products because the difference in packaging concepts is large. In table 5, the modeled service categories are given.

We distinguish packaging of carbonated beverages from packaging of noncarbonated beverages because not all packages suitable for noncarbonated beverages are also suitable for carbonated beverages, because of differences in the required barrier properties. The category "packaging of dairy products, other than milk" is modeled to take the consumption of polystyrene (PS) and polypropylene (PP) cups into account

these packaging processes but also by many other parameters that are included in the model, such as emerging technologies and changing resource costs. To discuss all model input in this article is not possible. For descriptions of the data inputs, we therefore refer to the work of Kok and Ybema (1997), Ybema and colleagues (1997), Hekkert and Worrell (1997), Hekkert and colleagues (1998), Joosten (1998), Gielen (1997), Daniels and Moll (1997), and Bouwman and Moll (1997). Furthermore, the full database and the model output files are available via the Internet (ECN 1999). A detailed discussion of modeling results for other product and materials life cycles can be found in the work of Gielen and Pieters (1999).

To provide some insight into the general ideas about energy use, supply, and efficiency in the future, economic development and future ways of material management that are the backbone of the model, we refer to table 4. In this table, we have listed a number of parameters that have

Table 4 Characteristics of the MATTER-MARKAL model for the year 2030

Parameter	Unit	Quantity
GDP growth	(%/yr)	2
Physical demand growth	(%/yr)	0.5
Fossil fuel prices growth	(%/yr)	0.7
Discount rate	(%/yr)	8
Average efficiency for electricity from fossil fuels	(% LHV)*	60
Nuclear energy	(% base case energy use)	6
Cost-effective energy efficiency improvement	(% 1990 efficiency)	25
CO_2 storage	(% base case emissions)	12
Biomass potential	(% base case energy use)	25
Other renewables	(% base case energy use)	15
Energy use truck transport	(% 1990 energy use/ton·km)	60

Note: GDP = gross domestic product, LHV = lower heating value.

*Efficiency is calculated based on LHV.

Table 5 Packaging service categories and demand trends in the MATTER model (index)

Cat. no.	Packaging service category	Unit	1990	2020	2050
1	Packaging of carbonated beverages	Liters of product	100	117	131
2	Packaging of noncarbonated beverages	Liters of product	100	120	139
3	Packaging of dairy products, other than milk	Liters of product	100	132	163
4	Packaging of wet food	Liters of product	100	152	204
5	Packaging of nonsusceptible dry food	Liters of product	100	112	125
6	Packaging of susceptible dry food	Liters of product	100	152	204
7	Packaging of nonfood liquids	Liters of product	100	151	203
8	Packaging of dry nonfood	Liters of product	100	111	123
9	Carrier bags	Bags	100	115	130
10	Industrial bags	Tons of product	100	157	213
11	Transport packaging	Liters of product	100	142	185
12	Pallet wrapping	Trip units	100	175	250
13	Pallets	Pieces	100	125	150

Note: The growth of the demand for packaging services is indicated by means of indices. The actual demand for 1990 is estimated based on packaging consumption data and demand data for specific product groups. Hekkert (2000a, 2000b) described the modeled demand and all assumptions to calculate that demand.

that are specifically used for this purpose, for example, packaging of margarine and yogurt. We establish a category called "packaging of wet food" to model high-strength packages such as steel food cans and glass jars. Further, we distinguish two types of dry food packaging: packaging of nonperishable dry food and packaging of perishable dry food. These packaging types differ in the barrier characteristics needed to pack susceptible and nonsusceptible food products. We distinguish between packaging of nonfood liquids and beverage packaging because of different legislation concerning recycled material content. We differentiate between carrier bags and industrial bags because the strength characteristics of industrial bags are much higher than for carrier bags. We also make a distinction between pallets and transport packaging, where the latter represents tertiary packaging such as corrugated boxes and crates that are placed on pallets when transported. Finally we create the category of pallet wrapping. This represents both shrink films and stretch foils that are wrapped around loaded pallets to keep them dry and clean.

Because the economy in western Europe is expected to grow in the period 1990–2050, the demand for packaging services is expected to increase as well. Table 5 summarizes the modeled

growth factors for the different packaging service categories. In this study, gross domestic product is expected to increase by a factor of 3.5 in the period 1990–2050. Packaging services do not increase at the same rate as a result of a de-materialization of the economy. The consumption of food and beverages, a major packaging category, is generally stabilizing because of stabilizing population and stabilizing per capita food consumption. The remaining growth is to some extent caused by a shift from simple food ingredients (e.g., raw vegetables) to prepared ingredients (that require packaging), changing household size, and changing lifestyles. Differences in food and beverage categories are based on the demand growth rates during the last decade (EC 1997). Higher growth rates are assumed for non-food packaging than for food packaging. Growth rates for these categories have been coupled with transportation growth rates.

Current and Future Packaging Technology

In the MATTER-MARKAL model, both current packaging practices and improved packaging technologies are modeled. Current packaging practices are modeled by defining representative reference packages within all packaging service categories. A reference package is a model package with average characteristics compared to packaging concepts currently used in western Europe. An example is the polyethylene terephthalate (PET) bottle with a volume of 1.5 L and a weight of 50 g to pack carbonated beverages. Future packaging technologies are modeled by defining material-efficient packages we refer to as "improved packaging." In the work of Hekkert and colleagues (2000a, 2000b), all references and improved packages that are modeled are described in detail. In this section, we give a short overview of the modeled packages. In table 6, all current and improved packages that are modeled are listed. The table also indicates for which packaging services the packages can be used. We now briefly describe the packaging concepts.

To pack carbonated beverages, steel or aluminum cans, as well as PET and glass bottles, are commonly used. The cans can be improved by reducing their weight. These developments are modeled by defining the improved packages as light cans. The lid of steel cans is normally made out of aluminum. This is problematic for recycling processes because aluminum incinerates in the recycling process. The all-steel can, with a lid made from steel, can be completely recycled and is therefore modeled as an improvement option.

Most PET bottles in western Europe are used only once. We modeled a 1.5 L single-use (one-way) PET bottle as a reference package. In several countries, reusable PET bottles are commonly used. Because these bottles make about 25 trips and are only twice the weight of single-use bottles, the material use per packaging service is a fraction of the original material use (Kort 1996). In addition, the reusable PET bottle can be made partly from recycled PET (Hunt 1994). This development is modeled as "improved PET bottle reusable."

Glass is a heavy material compared to alternatives such as the PET bottle, but it is still extensively used by the packaging industry. We have modeled both a large (1 L) bottle and a small (0.3 L) bottle that represent beer bottles. Large bottles can be made lighter (– 25%), and for the small glass bottle, reusable bottles are an option that is commonly used in some European countries (SVM 1994). For reusable glass bottles, we assume 20 return trips (Heineken consumer services).

The liquid board package is commonly used for milk and juice packaging. We have modeled two alternatives for the liquid board package: the pouch and the polycarbonate (PC) bottle. The pouch is a flexible polyethylene (PE) or polypropylene (PP) package that weighs only 4–10 g, whereas a liquid board package weighs 28 g (SVM 1994; Couwenhoven 1996). The PC bottle was introduced to the Dutch market in 1996 to replace the glass bottle. The PC bottle can be reused about 30 times before recycling the PC for other purposes such as fleece sweaters (Polycarbonaatfles in de winkel 1996).

Both PS and PP cups are used for packaging of margarine and yogurt products. We have modeled the substitution of PP cups for PS cups as an improvement option because PP cups are lighter than PS cups (12 and 14 g, respectively), furthermore the energy requirement to produce PP

Table 6 Current and improved packaging technologies and associated service categories (the service category numbers refer to the numbers in table 4)

Current packaging technology	Cat. no.	Future packaging technology	Cat. no.
Steel beverage can	1	Light aluminum can	1
Aluminum beverage can	1	Light steel can	1
		All-steel can	1
One-way PET bottle	1, 2	Reusable PET bottle	1, 2
		Improved reusable PET bottle	1, 2
Large glass bottle	1, 2	Light glass bottle	1
Small glass bottle	1, 2	Returnable small glass bottle	1
Liquid board package	2	Pouch	2, 7
		PC bottle	2
PS cup	3		
PP cup	3		
Glass jar	3, 4	Light glass jar	3, 4
Steel food can	4	Honeycomb steel food can	4
Cardboard box	5, 8	Light cardboard box	
Cardboard box plus bag	5	Light cardboard box plus bag	
PVC box	5, 8	Cardboard blister	8
LDPE film	5, 8	Metallocene film	5, 8
PP film	5, 8		
Paper packaging	5, 8		
PP laminate film	6	Metallocene: laminate film	6
PET laminate film	6		
PP metalized film	6	Metallocene: metalized film	6
PET metalized film	6		
HDPE bottle	7	Recycled HDPE bottle	7
		Liquid board package	7
PE carrier bag	9	Recycled PE carrier bag	9
Paper carrier bag	9	Multiple-use carrier bag	9
PE industrial bag	10	One-way FIBC	10
Paper industrial bag	10	Returnable FIBC	10
Corrugated box	11	Improved corrugated box	11
Cardboard crate	11	Plastic crate	11
Shrink foil	11	Wooden crate	11
One-way wooden pallet	12	Returnable PE pallet	12
Returnable wooden pallet	12	Recycled PE pallet	12
One-way PE pallet	12	Recycled PC pallet	12
		Corrugated fiberboard pallet	12
		Pressed wood pallet	12
Shrink cover	13		
Stretch film	13		

Note: The costs and energy requirements for these packaging concepts are determined by costs and energy use for material manufacturing, product assembly, transport, waste management, and recycling. See the work of Hekkert (2000a, 2000b) for these figures. PET = polyethylene terephthalate, PS = polystyrene, PP = polypropylene, PE = polyethylene, LDPE = low-density polyethylene, HDPE = high-density polyethylene, PVC = polyvinylchloride, PC = polycarbonate, FBIC = flexible intermediate bulk container.

is lower than for PS. Finally, the glass jar is modeled as an alternative package.

The glass jar is also suitable for packing of wet food such as jelly and canned vegetables. In this category it competes with the steel food can. Both the steel food can and the glass jar can be made lighter. For the steel food can, it is possible to use a honeycomb structure to make the can lighter without compromising its strength (Meert 1995).

For packaging of dry food products, both cardboard boxes and flexible packaging can be used. Commonly used flexible packages are foils and bags made out of low-density PE (LDPE) or PP. The thickness of the films is expected to decrease in future years because of the introduction of a new catalyst that improves polymerization control (metallocene films) (Stijn 1996). The weight of cardboard boxes can be decreased by 20% by removing unnecessary material, increasing product quantity, removal of outer boxes, and using thinner cardboard (SVM 1993, 1994).

Besides cardboard boxes, plastic boxes are used for packing of foodstuffs. We have modeled a polyvinylchloride (PVC) box. The same model box is used as a representative for blister packaging for nonfood purposes. The blister package can be improved by replacement of the PVC blister by an all-cardboard blister. This type of substitution is a clear trend in the do it yourself sector in the Netherlands (SVM 1995; van der Kort 1992).

Plastic films can also be used to pack susceptible foodstuffs. In that case they are often laminated or metalized to improve the barrier characteristics of the films. These very thin films can be made even lighter by using metallocene films.

For nonfood liquids such as shampoos and detergents, high-density PE (HDPE) bottles are often used for packaging because these bottles are cheap and do not need specific barrier characteristics. The standard HDPE bottle can be improved by using recycled material. It is also possible to replace the bottle by a liquid board package (Stijn 1996).

Carrier bags are most often made out of PE, whereas a small percentage are made from paper. Improvement options are using recycled PE and the introduction of a multiple-use carrier bag.

Industrial bags are also most often made out of PE, but for cement and fertilizer, paper bags are often used. As an improvement option, the flexible intermediate bulk container (FIBC) is modeled. FIBCs are very large and very strong bags (capable of carrying 1000 kg) made out of PP straps (van Well 1997). Most FIBCs are used only once, but multiple-use FIBCs are in use as well (van Well 1997).

Transport boxes are most often made out of corrugated board. Less corrugated board can be used for the same packaging service by many of the same measures as described for cardboard boxes (SVM 1994, 1995, 1996). Improvements in the primary packages may also lead to smaller corrugated boxes. We have modeled these developments by defining a light corrugated box that weighs 20% less than the reference box. In some cases, the corrugated box can be replaced by shrink film to bundle multiple primary packages (SVM 1993, 1994). Other improvements are the use of multiple-use (plastic) crates (Aysford 1995). These crates compete in other sectors (fruit and vegetable sectors) with wooden multiple-use crates and cardboard single-use crates (Dijk 1992).

Pallets are generally made out of wood. Two-thirds of the wooden pallets are used once; the rest are reused. On average, these pallets make about 40 trips (Berg 1996, Belkom 1994). Wooden pallets are in competition with multiple-use plastic pallets (either from PE, recycled PE, or recycled PC) and with corrugated fiberboard and pressed wood pallets that have lower trip numbers (one and five trips, respectively) (Witt 1990).

To bundle boxes on a pallet or to protect them from weather, both stretch films and shrink covers are used. Both can be made thinner, and in the case of stretch film, the amount of film used can be decreased by using more efficient wrapping machines (Zoethout 1997). These developments are modeled by defining lighter films.

Model Runs

In the introduction, we raised several questions that can be answered through an integrated analysis of improvements in the energy and materials systems of an economy. In our analysis, several model runs have been used to answer the questions. The model runs are related to different material management strategies and are described in table 7.

In the model runs we conducted, three variables were included. The first variable is the final demand for packaging. The final demand for packaging services has been set to zero in the runs excluding packaging demand. As a consequence, the production and waste handling of packaging materials is omitted from the energy and materials system, including all upstream and downstream emissions. The emission difference in the model runs with and without packaging demand (FE versus FE-NP, no-cost versus no-cost NP, etc.; see table 7) is a measure of the emissions contributed by packaging. An emission penalty of 100 EUR/ton (1 EUR is approximately 0.9 USD) can be seen as a realistic penalty when significant GHG emission reductions are targeted. The 500 EUR/ton penalty is not realistic, but the technical limits of emission reduction are analyzed by means of this penalty.

The second variable is the autonomous development of the improved use of materials. In the frozen efficiency (FE) run, all possible improvement options for packaging have been ex-cluded from the model. It simulates a situation where the packaging demand in 2030 is fulfilled by 1990 packaging technology and the 1990 demand structure. In the European Packaging Directive (EPD) run, the goals of the European Packaging Directive have been simulated. This implies a recovery of plastic waste of 65% and an average recycling rate of 35% (which is an important improvement compared to the current situation). The difference in emissions between the EPD and the FE run is an indication of the amount that GHG emissions can be reduced by adopting this waste management policy. The no-cost run is a model run where the model can choose from all available improvement options. The MATTER-MARKAL model works in such a way that all cost-effective measures are included in the base case of any model run. Many of the improved packages are cost effective and are therefore part of the no-cost run (Hekkert et al. 2000a, 2000b). The differences in model outcomes between the no-cost run and the EPD run are a measure of the additional GHG emission reductions that can be achieved by improving material management on top of the European Packaging Directive. It also shows which type of waste management is most effective for reducing GHG emissions.

The third variable is a GHG emission penalty. This penalty increases the costs of GHG emission, which will lead to shifts toward more efficient technologies and changes in fuel mix. The 100 EUR per metric ton CO_2 model run repre-

Table 7 Model runs for this study

Abbreviation	Name of model run	Final packaging demand	Efficiency improvement	Penalty (EUR/ton CO_2 equiv.)
FE	Frozen efficiency run	Included	None	–
EPD	Simulation of European Packaging Directive	Included	Due to packaging directive	–
No-cost	No-cost run	Included	All cost-effective measures	–
100P	100 EUR penalty run	Included	Due to penalty	100
500P	500 EUR penalty run	Included	Due to penalty	500
FE-NP	Frozen efficiency run excl. packaging	Excluded	None	–
EPD-NP	European Packaging Directive run excl. packaging	Excluded	Due to packaging directive	–
No-cost-NP	No-cost run excl. packaging	Excluded	Cost effective	–
100NP	100 EUR penalty run excl. packaging	Excluded	Due to penalty	100
500NP	500 EUR penalty run excl. packaging	Excluded	Due to penalty	500

sents a penalty level that is considered feasible in the framework of current emission reduction policies in Europe (Gielen 1998). The 500 EUR per metric ton CO_2 model run represents a very high penalty that is not feasible in the current policy discussion. Instead, it should be considered as a measure of the technical emission reduction potential. The penalties increase from zero in the year 2000 to their maximum level in 2020 and stabilize afterward.

Results

Figure 3 shows the GHG emissions from packaging for simulation of the increasingly stringent policy goals in the year 2030. The emissions related to packaging are calculated by subtracting the emissions from model runs that include packaging demand by the emissions from model runs that exclude packaging demand. The GHG emission in the EPD case is 130 MMT CO_2 equivalents. This is approximately 15 MMT less than the emissions in table 3, despite a doubling of packaging services. This decrease can be at-

tributed to expected autonomous efficiency gains in materials production and changes in waste management, and the impact of the packaging ordinance. Emissions decrease from a level of 130 MMT CO_2 equivalents in the EPD case, to 98 MMT in the no-cost case, to 85 MMT in the 100 EUR/ton penalty case, and to 55 MMT in the 500 EUR/ton penalty case. This is equivalent to an economic reduction potential of 25%, an economic reduction potential of 45% when CO_2 emissions are penalized by 100 EUR/ton, and a technological reduction potential of 58%,[12] simulated by a GHG-emission penalty of 500 EUR/ton CO_2. The difference between the EPD case and the no-cost case is completely accounted for by cost-effective measures that increase packaging efficiency. In other words, it is possible to reduce the materials-related GHG emissions by 25% on top of the effect of the European Packaging Directive by improving the material efficiency in material-product life cycles. Furthermore, emissions per ton of material decrease significantly when an emission penalty of 100 EUR/ton is introduced because of the introduc-
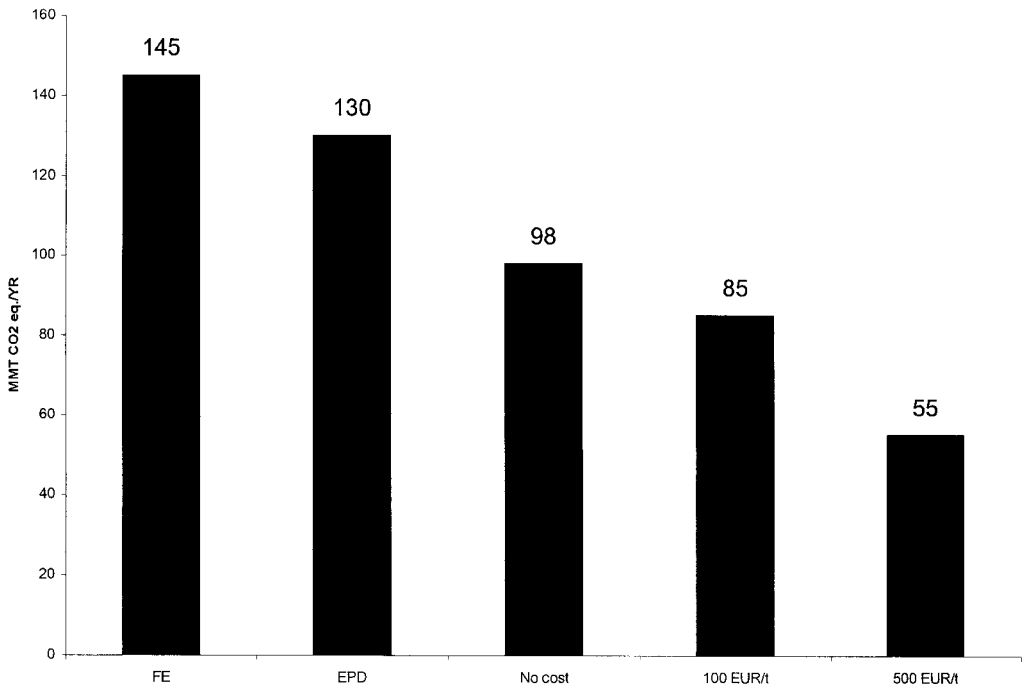

Figure 3   GHG emissions in the packaging life cycle for different model runs that simulate increasingly stringent GHG reduction policies, 2030.

tion of renewable energy, increased energy efficiency in materials production, and end-of-pipe technology for CO_2 removal and underground storage. The additional emissions reduction through materials substitution and product substitution is limited because most of these options are cost effective and therefore part of the base case. When an emission penalty of 100 EUR/ton is introduced, major waste handling changes occur. Methane is recovered from disposal sites, recycling rates are increased, and energy recovery from waste incineration is increased. The difference in GHG emissions between the 100 EUR/ton case and the 500 EUR/ton case can be attributed to a larger input of renewable energy and the large-scale input of renewable feedstock sources in the petrochemical industry. The fact that most material management options are part of the EPD case shows that material management options are low-cost options compared to many other GHG reduction options.

The impact of current waste prevention policies on GHG emissions is indicated by the difference between the EPD scenario and the FE scenario (– 10%). From this, we can learn that current waste prevention programs have a significant desirable effect on GHG emission reduction in the packaging life cycle.

Figure 4 shows the material use for packaging production for the different model runs that simulate increasingly stringent GHG emission reduction policies. The figure shows that the quantity of materials used in the EPD run are almost equal to those in the FE run. This can be explained by the fact that figure 4 shows the total materials use and not the primary materials use. In the EPD case, much more recycling takes place than in the FE case, but this does not affect the total material demand because recycling affects only the primary material demand. Figure 4 also shows that the amount of materials used is greatly reduced in the no-cost case compared to the EPD case (66 versus 83 MMT). This shows that efforts to reduce GHG emissions in material-product chains may lead to more significant waste reduction than does the European Packaging Directive. The reduction in material use is the result of shifts toward product reuse, material recycling, and the development of thin-

ner materials. The largest reduction is visible in plastics and glass production because of the fact that both materials are very suitable for product reuse. Plastics are partially replaced by wood. Therefore, the amount of wood is increasing. An emission penalty of 100 EUR/ton results in a material use of 59 MMT/yr: a reduction of 11% compared to the EPD case. Reduction in glass consumption is the main cause of the reduction in material use. Glass is replaced by (refillable) plastic packages and steel packages. The amount of steel packages increases because the CO_2 intensity of steel production is strongly reduced as a result of CO_2 removal when a CO_2 emission reduction penalty of 100 EUR/ton is introduced. The total amount of paper and board increases because it serves as a substitute for several types of plastic packaging.

An increase in the CO_2 emission penalty from 100 EUR/ton to 500 EUR/ton does not lead to a reduced use of materials. All available options for more efficient materials management are already implemented in the 100 EUR/ton case. Although the material consumption stays the same, the emission of GHGs does decline according to figure 3. As stated before, this reduction can be attributed to renewable feedstock resources and input of renewable energy (changes in materials production).

Table 8 shows how material and waste prices in the MATTER-MARKAL model are influenced by GHG emission penalties. The prices are significantly affected. Generally speaking, prices of materials and waste that lead to large GHG emissions are significantly increased when an emission penalty is introduced. Cost-effective GHG emission reduction options (with costs below the penalty level), however, may reduce the price increases. In the case of PP, the price effect is much larger than can be expected based on the associated GHG emissions. The reason is the coproduction of propylene and ethylene in the petrochemical industry. Although several alternative production routes are available in the model for ethylene production, no alternative routes have been encountered for propylene. To fulfill the propylene demand, large quantities of ethylene are produced. As a consequence, the model allocates the full burden of the coproduction
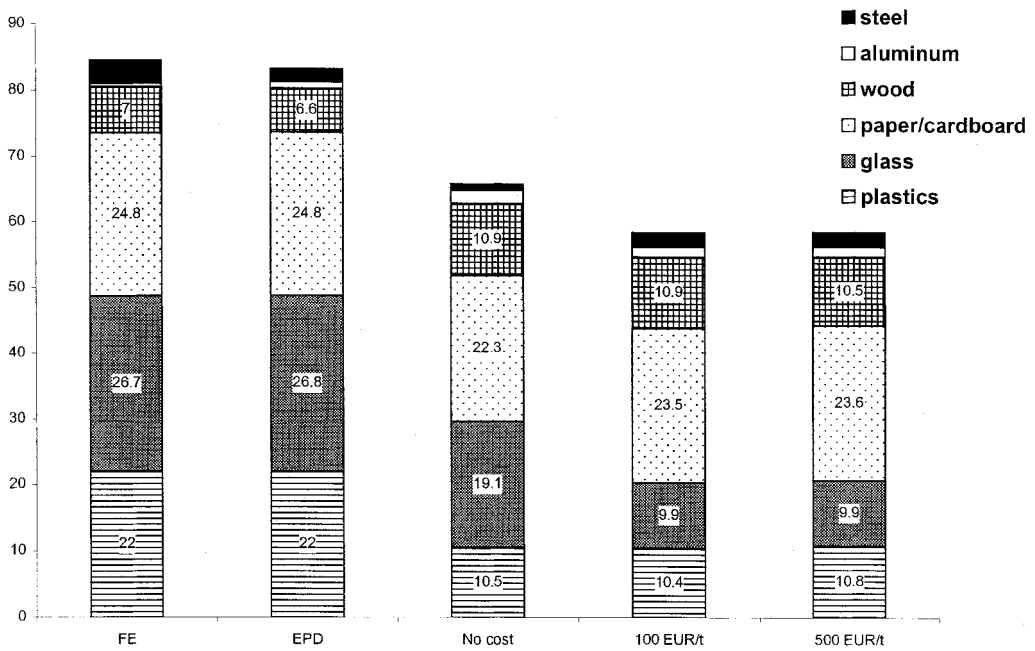
Figure 4 Shifts in packaging material use (expressed in million metric tons of material use per year) for model runs that simulate increasingly stringent GHG reduction policies, 2030.

Table 8 Changing prices due to GHG penalties, 2030

Material type	Basic product	Base case (EUR/ton)	Price (100 EUR/ton)
Metals	Cold rolled steel coil	326	436
	Steel scrap	100	118
	Primary aluminum ingots	2,182	3,079
	Aluminum scrap	1,524	2,341
Natural organic materials	Packaging paper	382	365
	Waste paper	− 47	− 98
	Sawn timber	311	337
Synthetic organic materials	Polyethylene	409	349
	Polypropylene	670	1,126
	PE/PP waste in MSW	− 365	− 595
	PET	894	1,106
	Clean PET waste	186	372

Source: Gielen and Pieters (1999).

Note: PET = polyethylene terephthalate, PP = polypropylene, PE = polyethylene, MSW = municipal solid waste.

emissions to the propylene production, which results in large price effects. Also, note the significant price effects for waste materials. Because of the GHG emission reduction effect of recycling waste materials, the prices become less negative (packaging paper) or even positive (PET, steel, and aluminum). On the other hand, the price of plastic waste in municipal solid waste decreases dramatically because of the comparatively low efficiency of energy recovery from that waste. The increased value of certain waste materials makes increased waste collection and expensive recycling technologies cost effective.

The impact on packaging services is less pronounced than the impact on packaging materials (figure 5). The reason is that additional costs for packaging manufacturing and packaging handling consist mainly of labor and capital costs. These production factors are characterized by low GHG emissions per monetary unit, in comparison to energy and materials. This effect reduces the incentive for materials substitution by packaging consumers (i.e., product producers).

In discussions regarding environmental impacts of packaging, plastics are often seen as the most problematic materials. Even though this might be true for a number of reasons such as that plastics are difficult to recycle, one should keep in mind that the emission accounting in the life cycle of plastics is complicated by the fact that carbon is stored in synthetic organic materials, which is released only if these materials are incinerated. Moreover biomass feedstocks can be applied in order to produce biochemicals. As a consequence, the emissions in the life cycle of plastics will decrease dramatically. The emissions in the life cycle of western European petrochemical products decrease by a factor of 2 when an emission penalty of 200 EUR/ton is applied in the model (Groenendaal and Gielen 1999). Such reductions compete with materials substitution as a strategy for reducing emissions in the life cycle of plastic packaging; however, the results show that materials substitution is considerably cheaper than emission reductions in materials production.
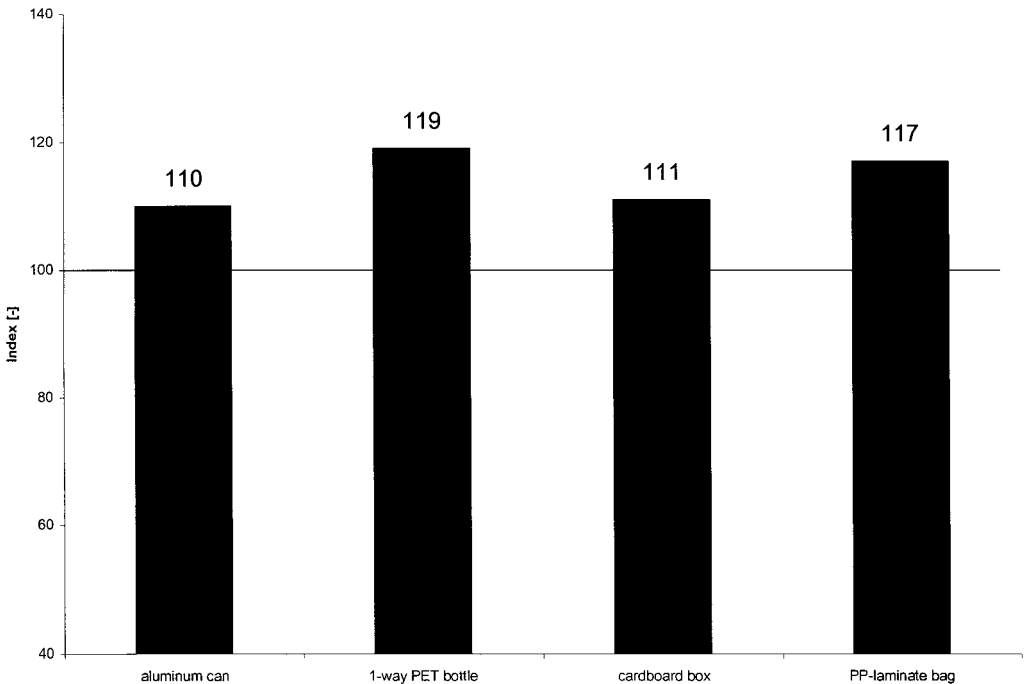

Figure 5   Changing packaging service costs, 100 EUR/ton penalty scenario, 2030 (base case =   100).

Discussion

The results of our study show a reduction in GHG emissions of 32% in the no-cost run relative to the FE run and a 25% reduction relative to the EPD run. These reductions can be attributed to material management options. The 100 EUR/ton run shows further reductions (41% compared to the FE run), but not all of these reductions are related to changes in the materials system. Earlier studies show a reduction in GHG emissions of 40% for transport packaging and 51% for primary packaging (Hekkert et al. 2000a, 2000b). The total reductions related to changes in the material system is smaller than 40% in this study and therefore smaller than expected based on the other two studies. This can be explained by the longer time frame of this study compared to the other two, which leads to higher efficiencies in energy conversion, new material production technologies, and more efficient waste management practices. Materials efficiency options prove to be considerably cheaper than emission reduction options in materials production or emission reductions in the energy system. The reliability of the results depends on the input data and the methodology that is used in the model. We discuss both aspects.

The packaging input data are detailed but still limited in comparison with the actual complexity. This may affect the emission reduction potential, but whether this impact is positive or negative is not clear. For an extensive discussion on the influences of the quality of the packaging data on the final results, please refer to work of Hekkert and colleagues (2000a, 2000b).

It is always difficult to make a forecast about the future efficiencies and costs of new technologies. Large uncertainties are introduced when using data on technologies that are still in an early stage of development. This is a problem for any long-term technology assessment study. Because the model mainly provides insight with regard to mechanisms, absolute numbers should not be applied for policy making. Although some technology assumptions may be too optimistic, other important efficiency opportunities may be overlooked. The same may be true with regard to long-term socioeconomic trends.

Besides data input, the model characteristics influence the reliability of the results as well. The MARKAL model is based on an assumption of a perfect market. In fact, monopolies and oligopolies are common, especially in the capital-intensive materials-producing industry and in waste management. With regard to materials use, the large diversity is probably better reflected by MARKAL. Finally, the model does not account for carbon leakage (relocation of materials-producing industries to other regions) or for large changes in product demand due to increasing prices caused by CO_2 policies. Both effects may be substantial, as shown in several recent studies (Gielen and Pieters 1999; Gielen 1999).

Conclusions

Packaging materials currently constitute approximately 3.3% of the total GHG emissions and 14% of the material-related GHG emissions in western Europe. Packaging services are growing rapidly, but there is ample room for improved management of materials, such as materials substitution, increased material recycling, and product reuse.

The results show that for the year 2030, a cost-effective GHG reduction potential of 25% compared to the EPD model run where the current goals of the European Packaging Directive are simulated and a 32% reduction compared to the FE scenario. This suggests a very significant no-regret potential for emission reduction in the packaging chain, based on increased materials efficiency. If a GHG emission reduction penalty of 100 EUR/ton is introduced, a GHG reduction of 45% is achieved compared to the EPD scenario. A technological improvement potential of 58% is calculated by introducing a GHG emission penalty of 500 EUR/ton. Generally speaking, improved material management dominates the gains that can be achieved with or without low GHG emission penalties, whereas the reduction of emissions in materials production and the reduction of emissions in waste handling dominate when high GHG penalties are applied.

The results suggest that more attention should be paid to material efficiency improve-

ment in climate change policy because of the technical potential and the low life-cycle costs of material efficiency improvement compared to other GHG emission reduction measures. In other words, instruments such as integrated chain management, material-efficient product design, design for the environment, and extended producer responsibility might be very effective and efficient ways to contribute to GHG emission reduction.

The costs of materials efficiency improvements are considerably lower than the costs for emission reductions in materials production. Moreover, secondary benefits such as reduced resource consumption and other environmental benefits have not been accounted for in this analysis. The mix of "best" emission reduction options is influenced by the interactions in the energy and materials system. It is essential to account for such interactions in the development of long-term emission reduction strategies. Any policy that focuses on specific sectors is likely to be suboptimal. The extent of this suboptimality depends on the specific sector. Such effects are very likely in the life cycle of bulk materials. As a consequence, the current practice of voluntary agreements with materials-producing industries to reduce their GHG emissions may be reconsidered in favor of more generic approaches that account for interactions in the material system (e.g., a materials tax in combination with measures to prevent a distortion of international competitiveness).

Policies directed at waste reduction also lead to GHG emission reduction and vice versa. The EPD scenario, which simulates the goals of the European Packaging Directive, shows a 7% GHG emissions reduction in comparison to the frozen efficiency run. GHG emission reduction goals, however, may lead to more significant waste reduction than would the European Packaging Directive. According to our study, the EPD results in a decline of materials consumption by 2 MMT, whereas a 100 EUR/ton CO_2 penalty results in a decline by about 10 MMT. In conclusion, we find that integration of several (inter)national policy areas such as GHG emission reduction policies, waste reduction policies, and product policies may be an effective and efficient

way to achieve both GHG emission reduction and waste minimization.

The added value of the MARKAL approach is that the interactions of emission reduction strategies are considered. The improvements in energy efficiency reduce the emission reduction potential of materials production and waste handling.

Acknowledgments

Notes

1. Improved material management = increased efficiency in material production, use, and waste management = material substitution + material recycling + improved product design, lightweighting + product reuse + material cascading.
2. All instances of "ton" refer to "metric ton" unless noted otherwise. 1 metric ton = 1,000 kg = 1 Mg = 1.1 short ton = 0.98 long ton.
3. The GHGs considered in the Kyoto Protocol are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).
4. Western Europe is defined as the European Union plus Norway, Switzerland, Iceland, and Liechtenstein.
5. The reference year is 1990 for CO_2, CH_4, and N_2O, 1995 for HFCs, PFCs, and SF_6.
6. CO_2 equivalent is a method for adding the emission of substances with different global warming potentials. The emissions of all substances are expressed in terms of CO_2 emissions with an equal effect on global warming.
7. This excludes transport to consumers and product manufacturing from materials.
8. The MATTER project involves three Dutch Universities (Utrecht University [STS], Free University in Amsterdam [CAV], and Groningen University [IVEM]), Bureau B&G, and the Netherlands Energy Research Foundation (ECN) and was carried out in the period 1995–1999. It is a follow-up project on a similar study done for just the Netherlands; see the work by Okken and Gielen (1994).

9. Table 3 presents a quick calculation of the relevance of materials in GHG emissions. It does not present a model outcome where practices such as energy recovery from waste incinerators are included. If this energy recovery had been taken into account, the emissions from waste paper and plastics would be significantly lower.

10. The average recycling rate of aluminum cans in western Europe is 35%, but individual countries recycle up to 90% (Sweden).

11. Introduction of GHG emission penalties results in higher costs for processes with large GHG emissions. Because the model calculates the lowest-cost system, other processes with lower GHG emissions may replace these processes.

12. A technological potential is defined as the achievable savings resulting from the most effective combination of the efficiency improvement options available in the period under investigation. An economic potential is defined as the potential that can be achieved at a net positive economic effect.

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